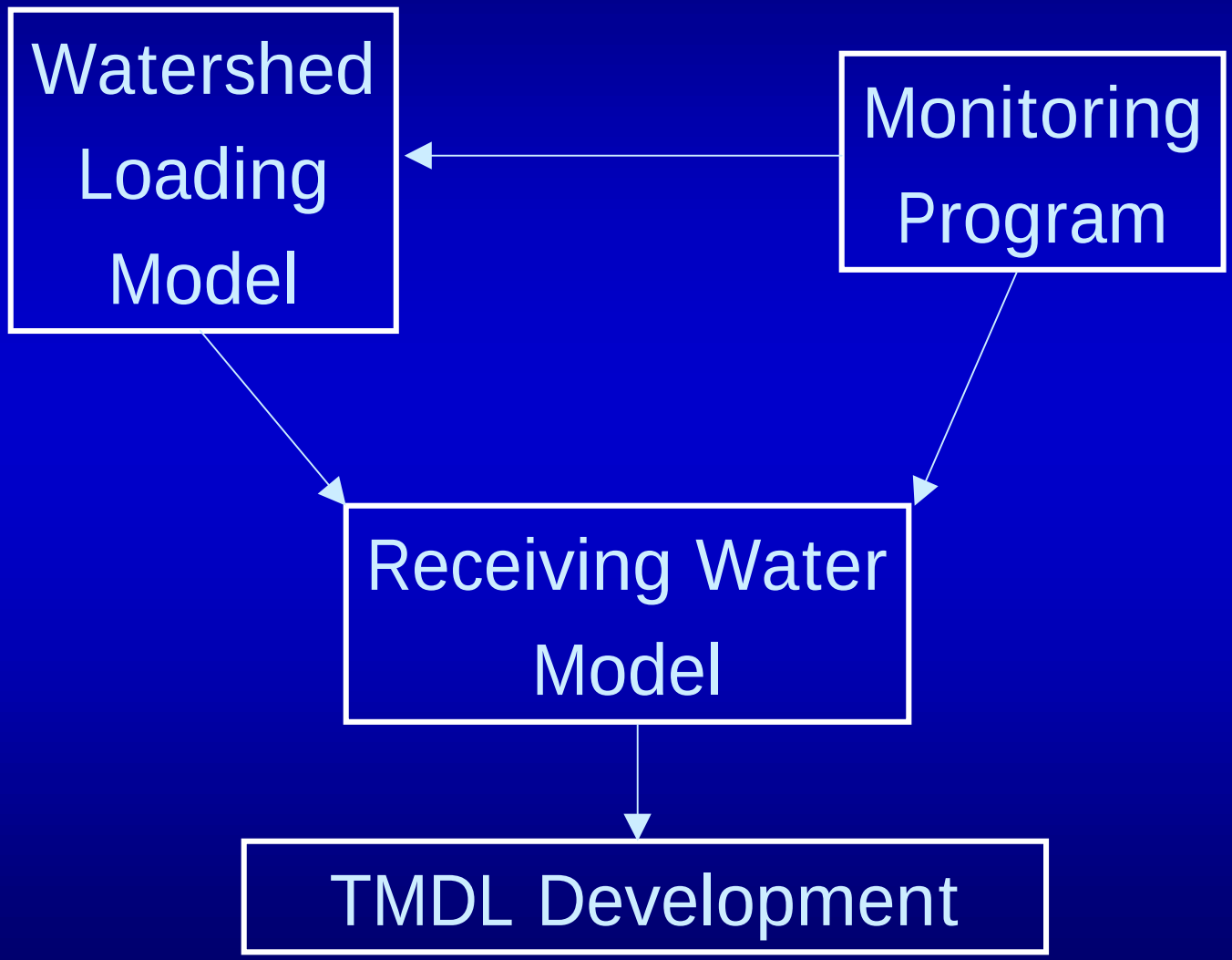
CHRISTINA RIVER WATER QUALITY MODEL

STUDY OBJECTIVES

- Provide a calibrated and validated hydraulic and water quality model of Christina River basin representative of critical low-flow conditions
- Provide a model capable of addressing variable flow conditions for next phase of the TMDL
- Provide training on the model use
- Develop TMDL allocation scenarios
- Technical report documenting the results

CHRISTINA MODELING EFFORT



AVAILABLE DATA

- Davis 1997 field study report
- GIS coverages including NPDES discharges, monitoring stations, HSPF watersheds, water withdrawals, etc.
- Pennsylvania, Delaware, and Maryland DMR data
- Tide data at Wilmington and Newport
- Diel oxygen data from USGS stations
- STORET data
- PCS data
- HEC-2 cross-section data from FEMA
- CBOD5, CBODu, DOC, TOC special study for large NPDES discharges

ORGANIC CARBON vs. CBOD

- Special study at 14 largest NPDES discharges
- Monitored on six separate days:
  - TOC (mg/L)
  - DOC (mg/L)
  - CBOD5 (mg/L)
  - CBODu (mg/L) - 20-day CBOD
- Used to calculate:
  - CBODu : CBOD5 ratio
  - DOC : TOC ratio
  - TOC : CBODu ratio

ENVIRONMENTAL FLUID DYNAMICS CODE

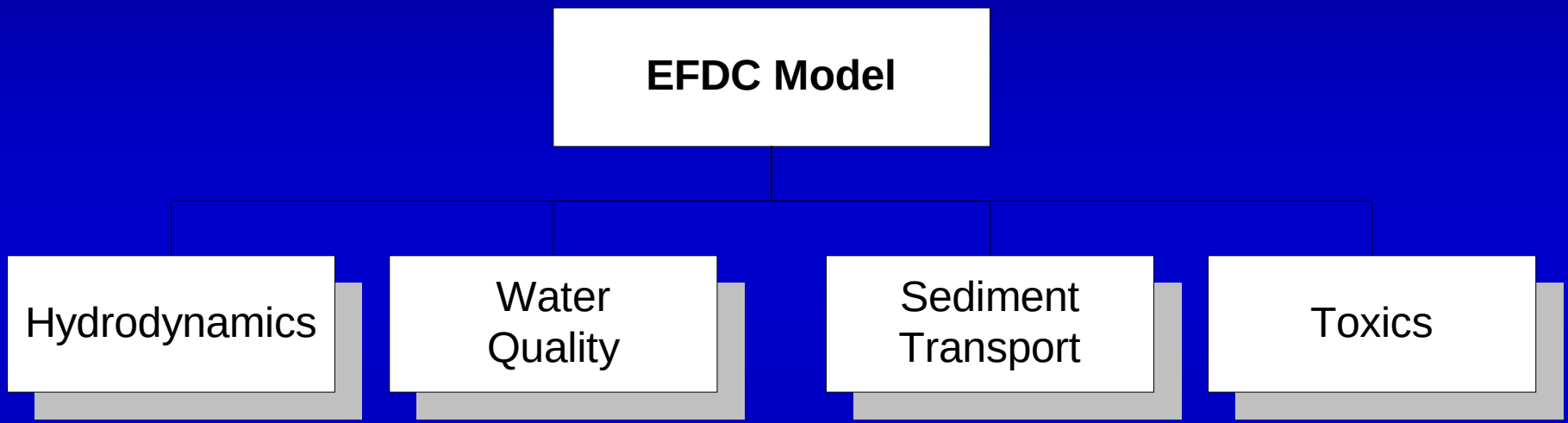
- The EFDC Model Is a Public Domain Surface Water Modeling System Incorporating Fully Integrated Hydrodynamic, Water Quality and Sediment-Contaminant Simulation Capabilities
- EFDC Is Extremely Versatile and Can Be Used for 1, 2, or 3-Dimensional Simulation of Rivers, Lakes, Estuaries, Coastal Regions and Wetlands
- The Single Source Code Implementation Eliminates the Need for Linking Multiple Models to Arrive at an Effective Modeling Solution

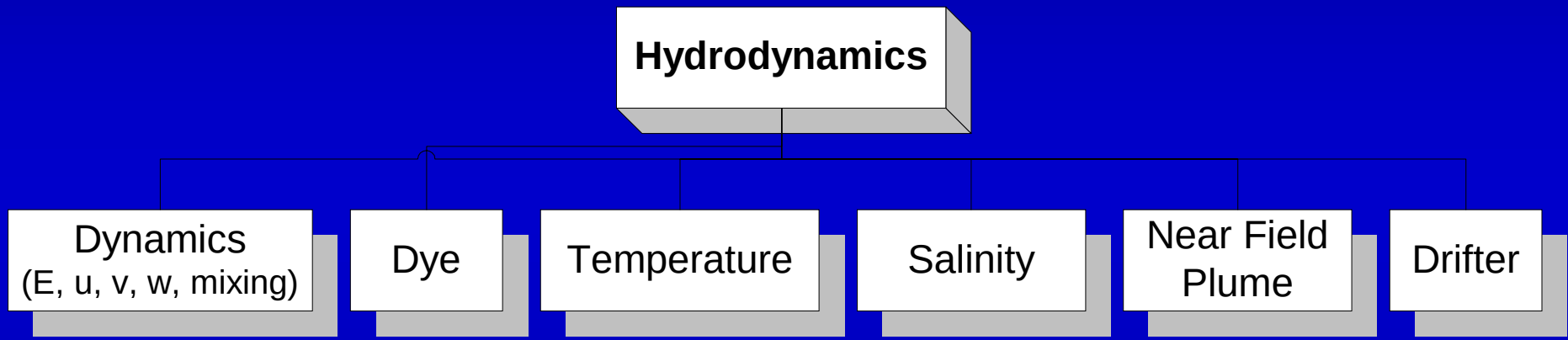
EFDC DEVELOPMENT HISTORY

- Developed at Virginia Institute of Marine Science with Primary Support from State of Virginia
- Additional Support from EPA and NOAA
- Presently Maintained by Tetra Tech, Inc.
- Currently used by Federal, State and Local Agencies, Consultants and Universities
- US EPA Currently Supporting Development of EFDC-Based Surface Water Modeling Toolkit

EFDC CAPABILITIES

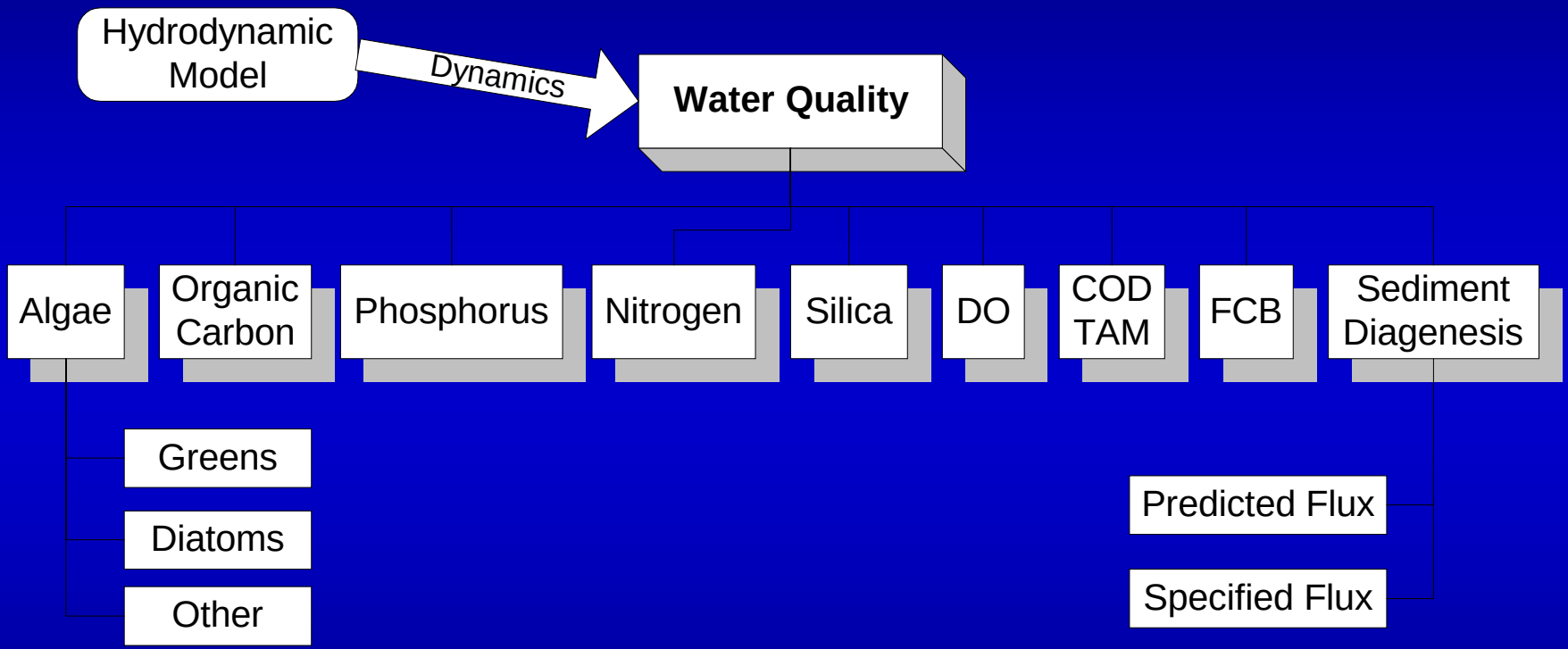
- Three-Dimensional Hydrodynamics with Coupled Salinity and Temperature Transport
- Directly Coupled Water Quality-Eutrophication Model
- Directly Coupled Toxic Contaminated Sediment Transport and Fate Model
- Integrated Near-field Mixing Zone Model
- Preprocessing Software for Grid Generation and Input File Creation
- Postprocessing Software for Analysis, Graphic and Visualization


EFDC Model
Hydrodynamics
Water Quality
Sediment Transport
Toxics


Hydrodynamics
Dynamics
(E, u, v, w, mixing)
Dye
Temperature
Salinity
Near Field
Plume
Drifter

EFDC WATER QUALITY-EUTROPHICATION

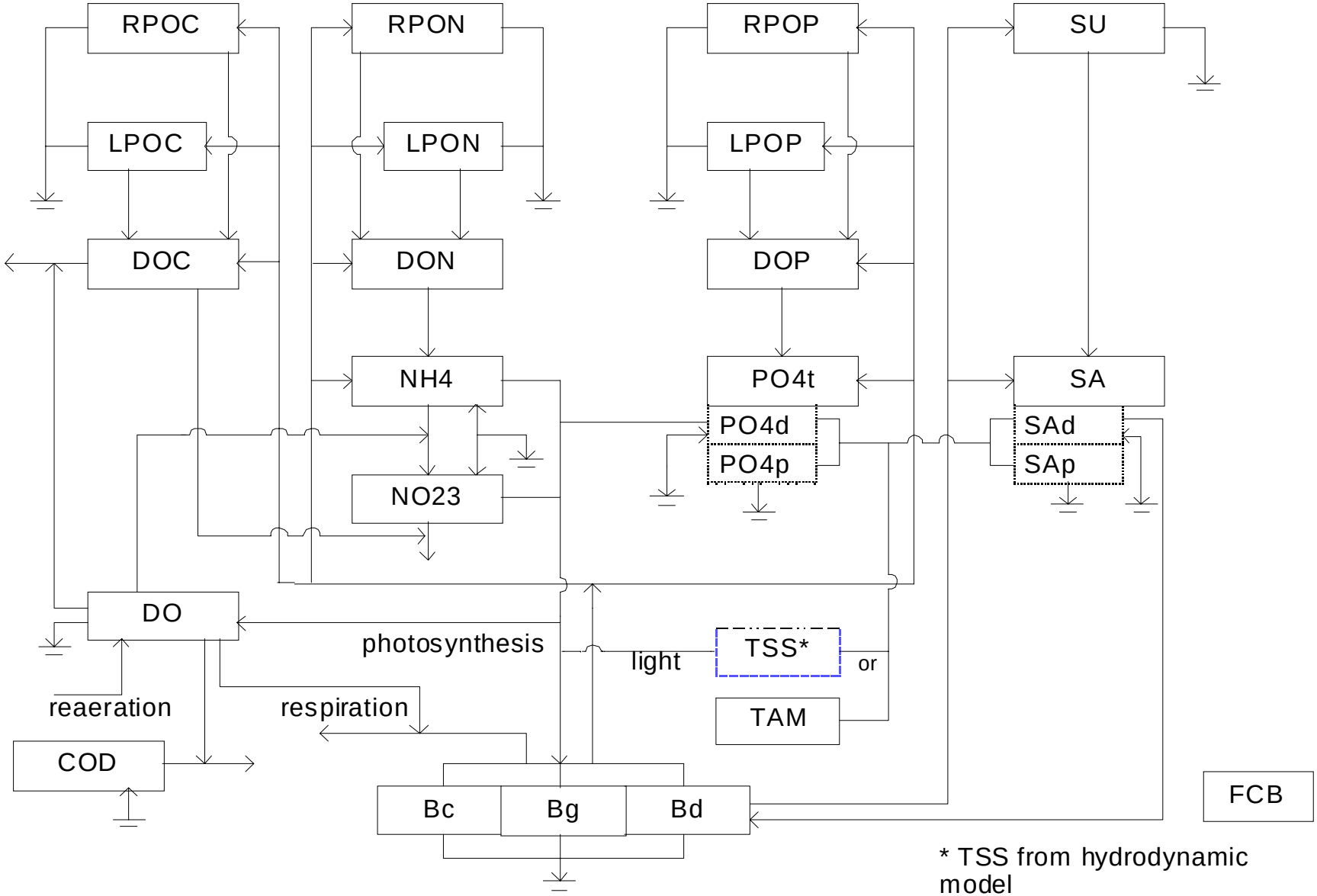
- Directly Coupled to Hydrodynamics
- Based on CE-QUAL-IC (Chesapeake Bay WQ Model) Kinetics
- 21 Water Column State Variables Including Multiple Classes of Algae and Organic Carbon, Nitrogen and Phosphorous
- Includes 27 State Variable Sediment Diagenesis Sub-model
- Reduced Number of State Variable Version Equivalent to WASP5


Hydrodynamic Model
Dynamics
Water Quality
Algae
Organic Carbon
Phosphorus
Nitrogen
Silica
DO
COD TAM
FCB
Sediment Diagenesis
Greens
Diatoms
Other
Predicted Flux
Specified Flux

EFDC WQ State Variables

1) cyanobacteria
2) diatom algae
3) green algae
4) refractory particulate organic carbon
5) labile particulate organic carbon
6) dissolved carbon
7) refractory part. organic phosphorus
8) labile particulate organic phosphorus
9) dissolved organic phosphorus
10) total phosphate
11) refractory part. organic nitrogen
12) labile part. organic nitrogen
13) dissolved organic nitrogen
14) ammonia nitrogen
15) nitrate nitrogen
16) particulate biogenic silica
17) dissolved available silica
18) chemical oxygen demand
19) dissolved oxygen
20) total active metal
21) fecal coliform bacteria
22) macroalgae

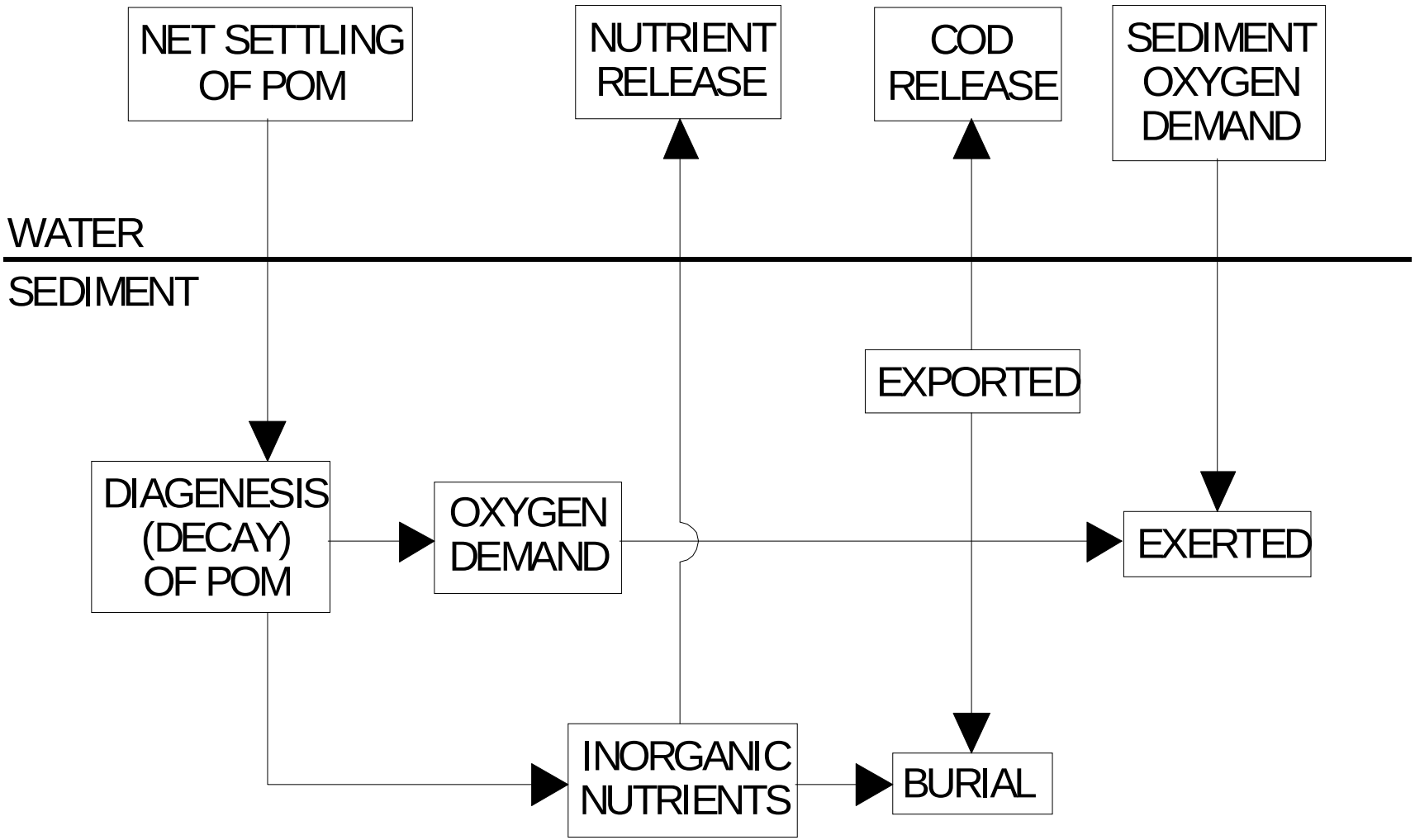
EFDC Water Quality Schematic

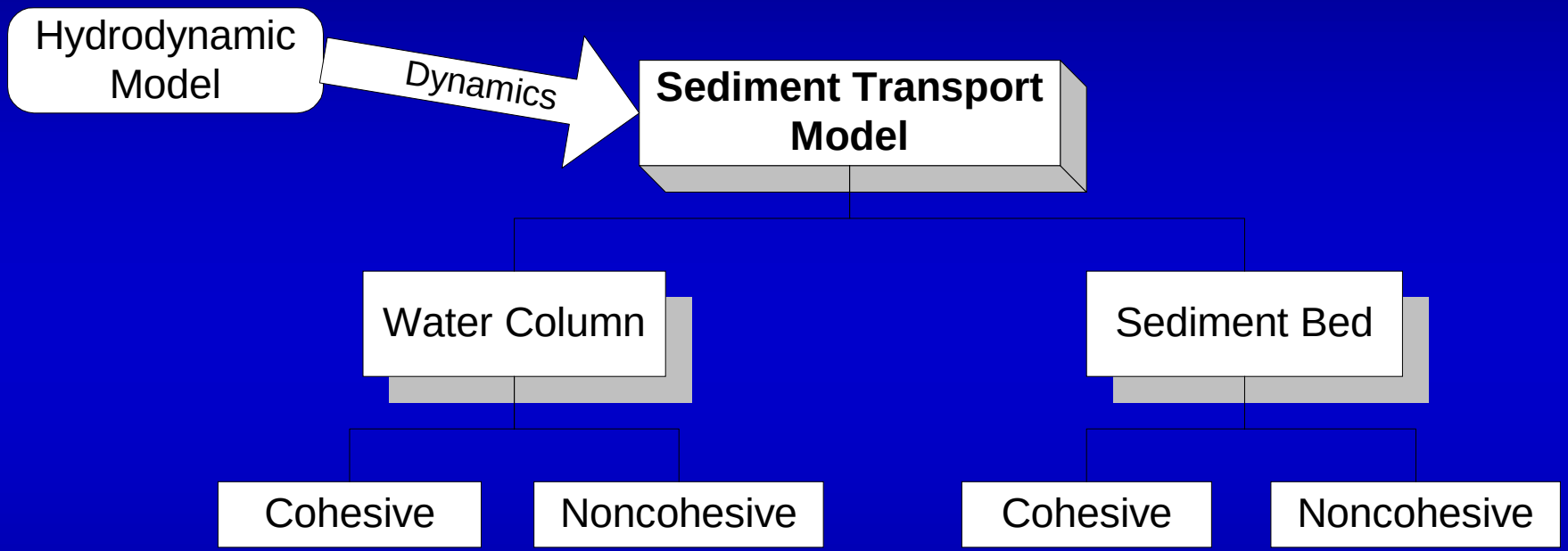


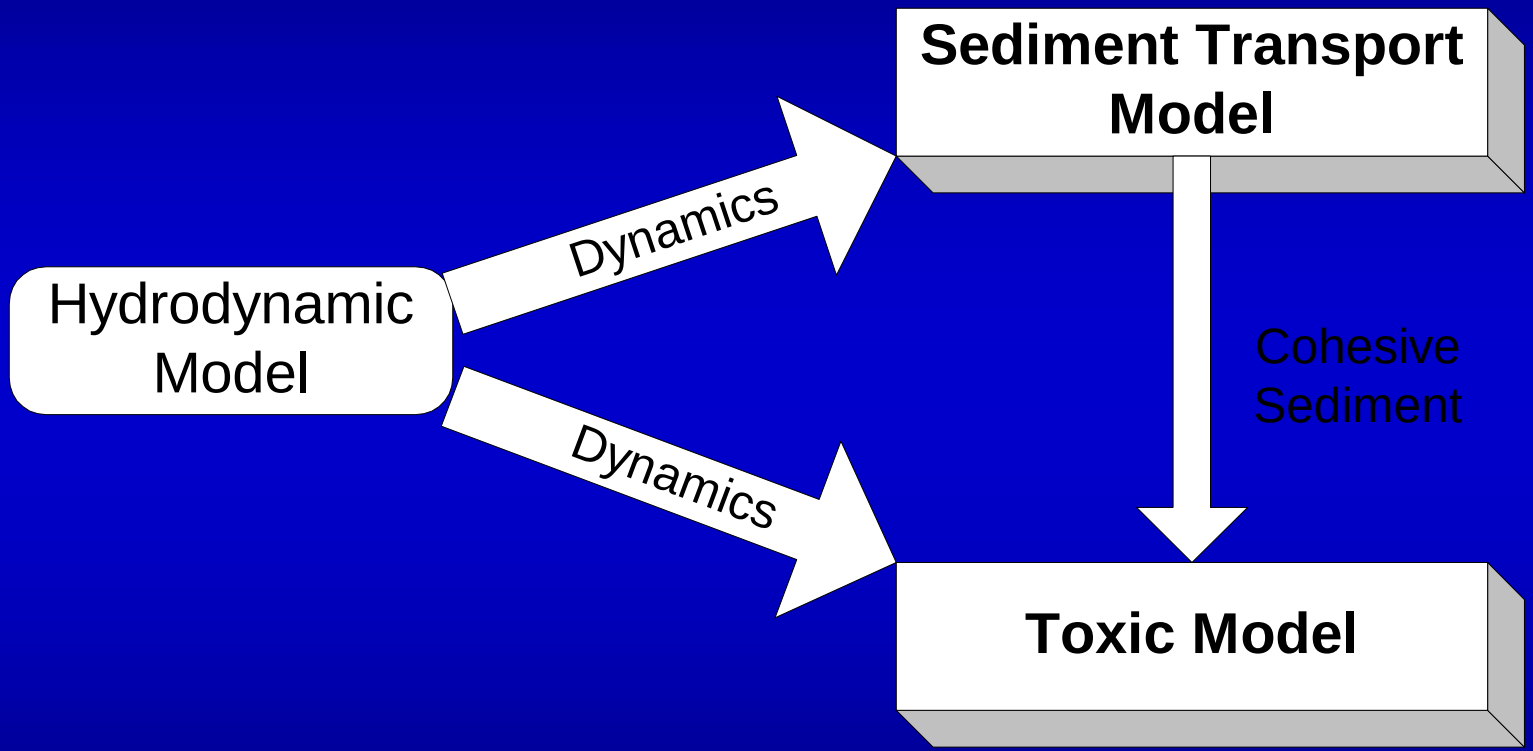
EFDC SEDIMENT DIAGENESIS MODEL

- Developed by DiToro & Fitzpatrick for Chesapeake Bay Model
- 27 state variables and fluxes
- Three basic processes:
  - Depositional flux of POM from water column
  - Diagenesis (decay) of POM in sediments
  - Flux of substances produced by diagenesis
- Benthic sediments represented by 2 layers
  - Upper layer can be oxic or anoxic
  - Lower layer is always anoxic

Sediment Diagensis Model Schematic




Hydrodynamic Model
Dynamics
Sediment Transport Model
Water Column
Sediment Bed
Cohesive
Noncohesive
Cohesive
Noncohesive


Sediment Transport Model
Dynamics
Hydrodynamic Model
Dynamics
Cohesive Sediment
Toxic Model

WATER QUALITY MODEL

- 16 stream segments
  - Christina River (tidal and nontidal)
  - Brandywine Creek (tidal and nontidal)
  - East and West Branch Brandywine Creek
  - White Clay Creek (tidal and nontidal)
  - Red Clay Creek
  - Delaware River
- Designed to be linked to watershed runoff model for seasonal analysis

GRID REPRESENTATION

- 1D finite-difference grid cells in streams and tidal Christina River
- 2D finite-difference grid in Delaware River
- 406 grid cells, single vertical layer
- Cell lengths are 500 - 1000 meters
- Model boundaries are sufficiently far from mouth of Christina River to ensure boundary conditions do not impact study area

STREAM GEOMETRY

- HEC-2 data was used to determine channel geometry and stream slopes
- Channel slopes also determined from USGS quadrangle maps
- Channel lengths determined along meander of 1:100,000 DLG hydrography data
- Detailed cross-section data available for those locations in Davis 1997 field study

FLOW STRUCTURES

- 32 flow structures included in the model
- 8 tidal inlets to connect peripheral streams to Christina River
- 24 overflow structures representing low-head dams, submerged weirs, bridge culverts, fall lines, stream confluences
- Other dams on peripheral tributaries, such as Marsh Creek, were not included in EFDC model but will be considered in the watershed model
- Rating curve representing a free overfall was used for the overfall structures

HYDRAULIC FLOW BALANCE

- Flow balance checked actual dynamic simulation from May 1 to Sep 21, 1997
- Flow from contributing watersheds were based on drainage area
- The period August 1 - 31 was the focus of the calibration since this period approximated 7Q10 flow conditions
- Dynamic calibration will be refined after the watershed runoff model is completed

TIDE CALIBRATION

- Tide elevation data were available during the calibration period at Port of Wilmington and Newport
- Model boundary tides were simulated using the major harmonic constants M2, S2, N2, K1, and O1
- Calibration results for amplitude and phase agree very well (see Table 9-2)

Point Sources

- 122 NPDES discharges included in model
- Loads were developed based on DMR data available
- Detailed monitoring for 7 discharges included in the 1997 study (Davis)
- For NPDES discharges not included in DMRs, loads for model calibration were estimated based on characteristic concentrations and a flow rate of 75% of the permit limit flow

WATER QUALITY CALIBRATION

PARAMETERS

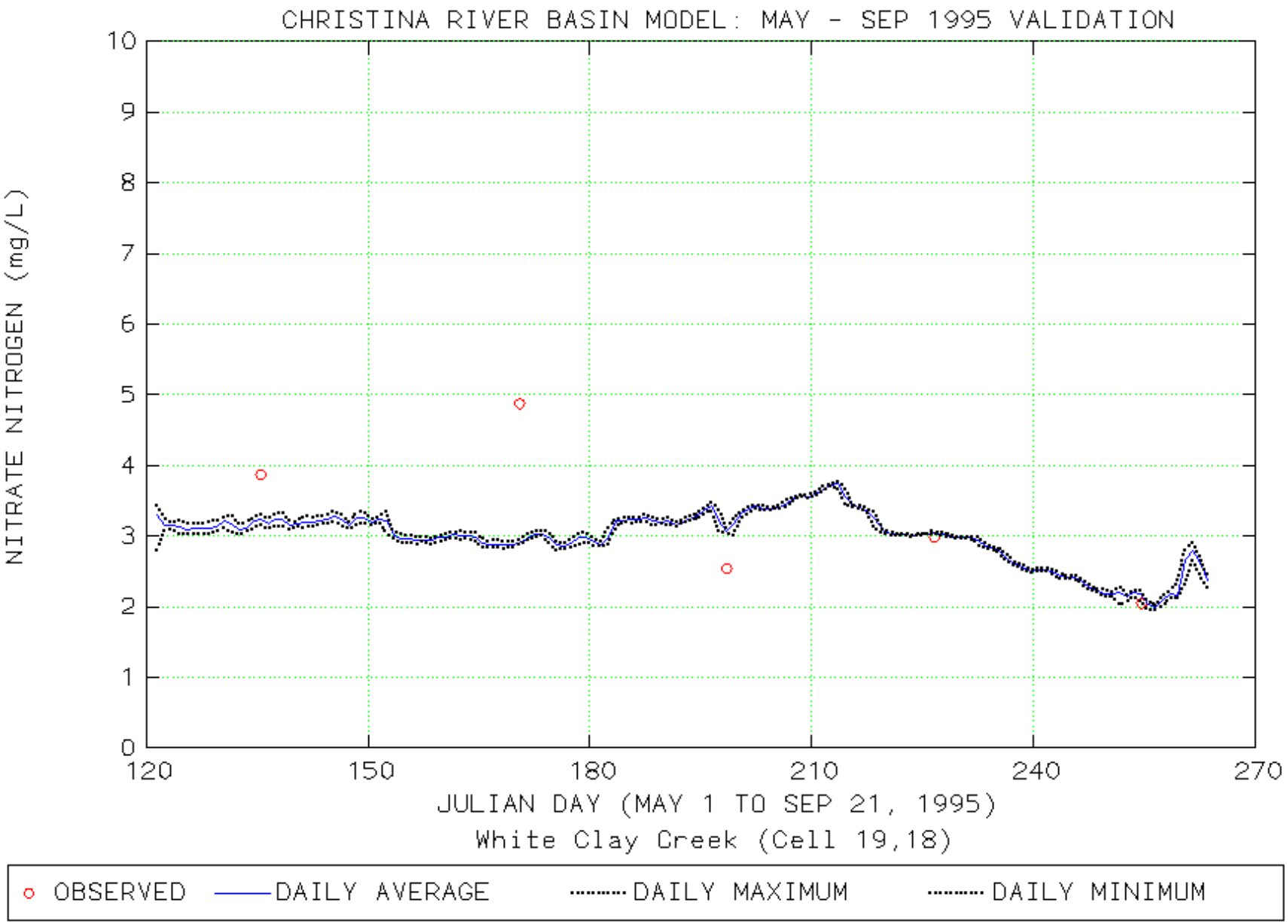
- Chlorophyll-a
- Nitrogen (ammonia, nitrate, total)
- Phosphorus (orthophosphate, total)
- Organic carbon (dissolved, total)
- Total suspended solids
- Chloride concentrations
- Daily average dissolved oxygen
- Diel dissolved oxygen (daily min/max)

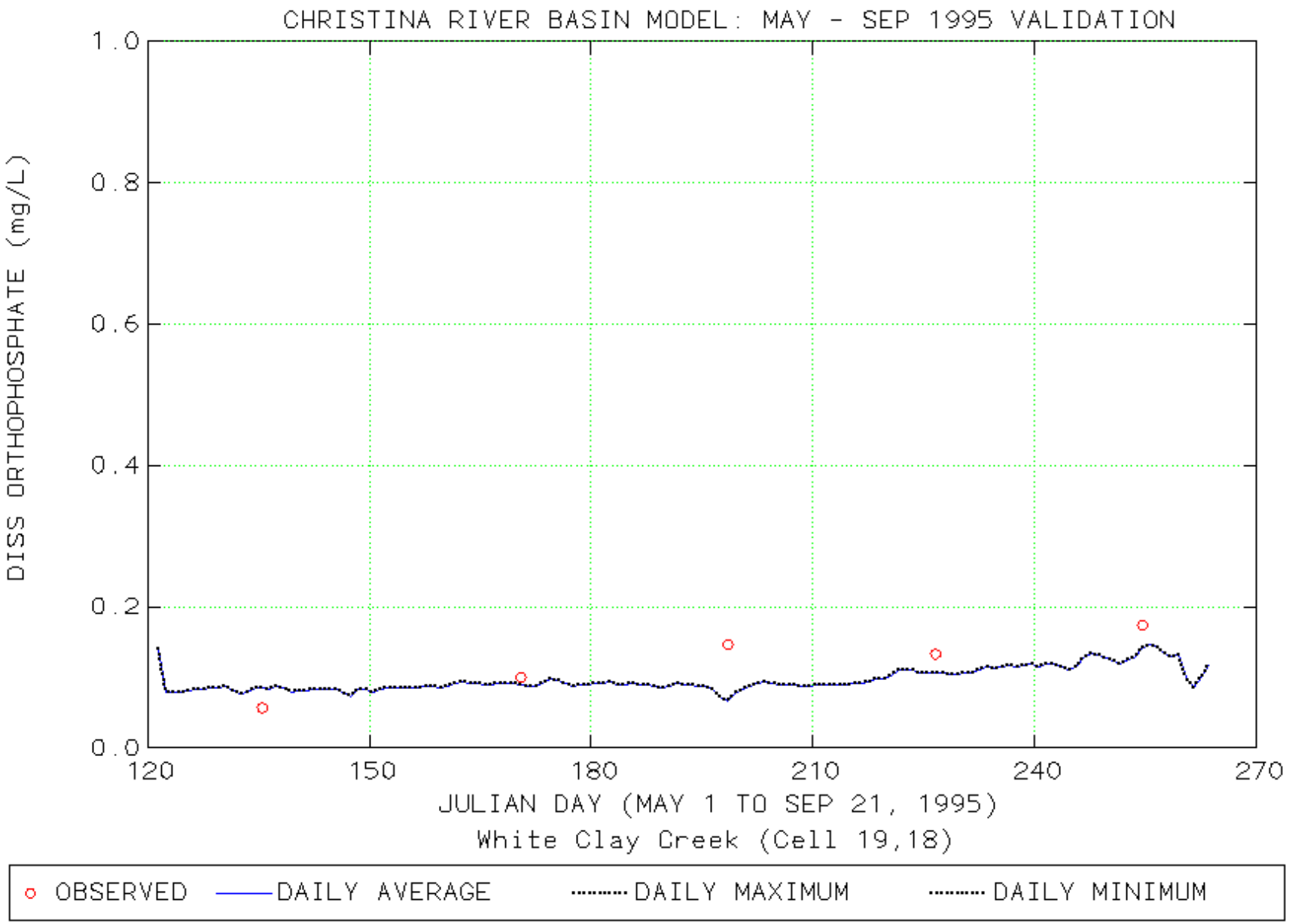
WATER QUALITY CALIBRATION

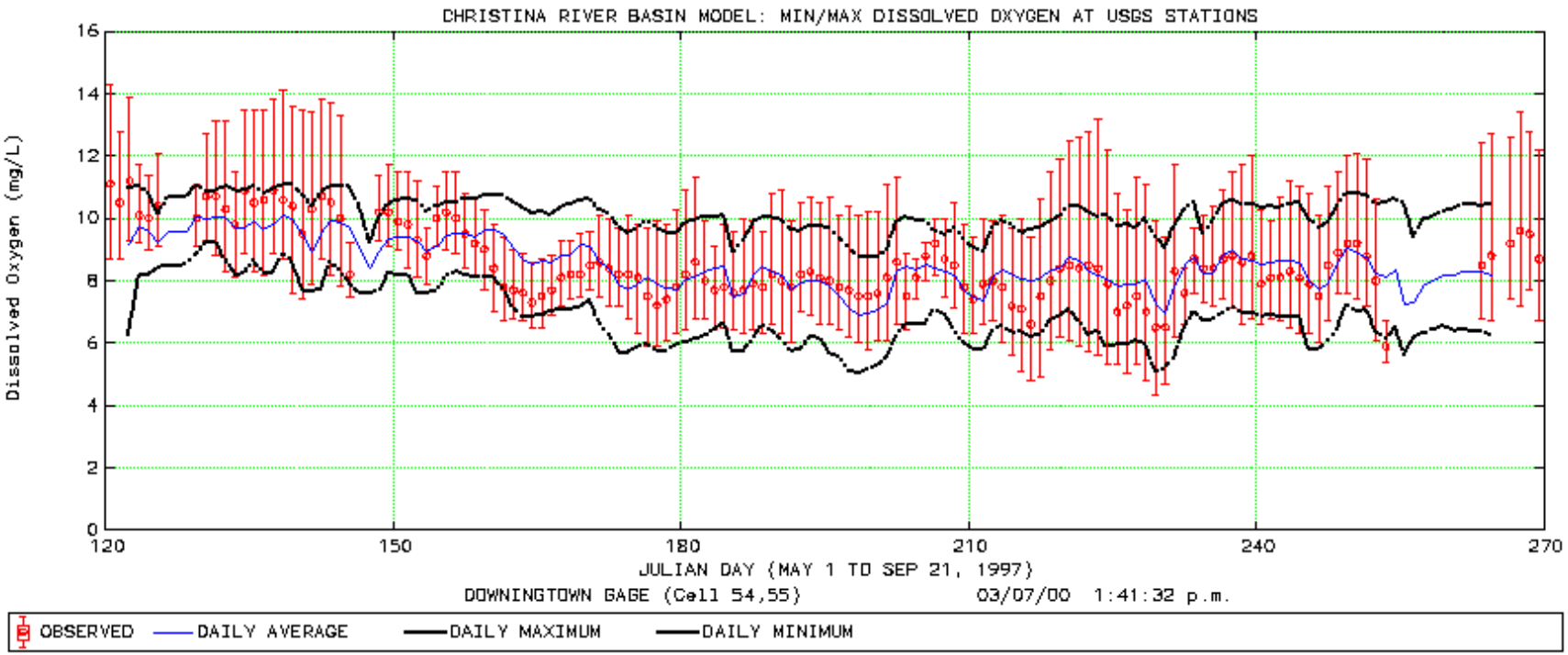
- Model calibration period was May 1 to September 21, 1997
- Model validation period was May 1 to September 21, 1995
- Nonpoint source loads from peripheral tributaries were computed using estimated 7Q10 flow rates and a characteristic concentration for each parameter
- Model-data statistics were computed and summarized in report

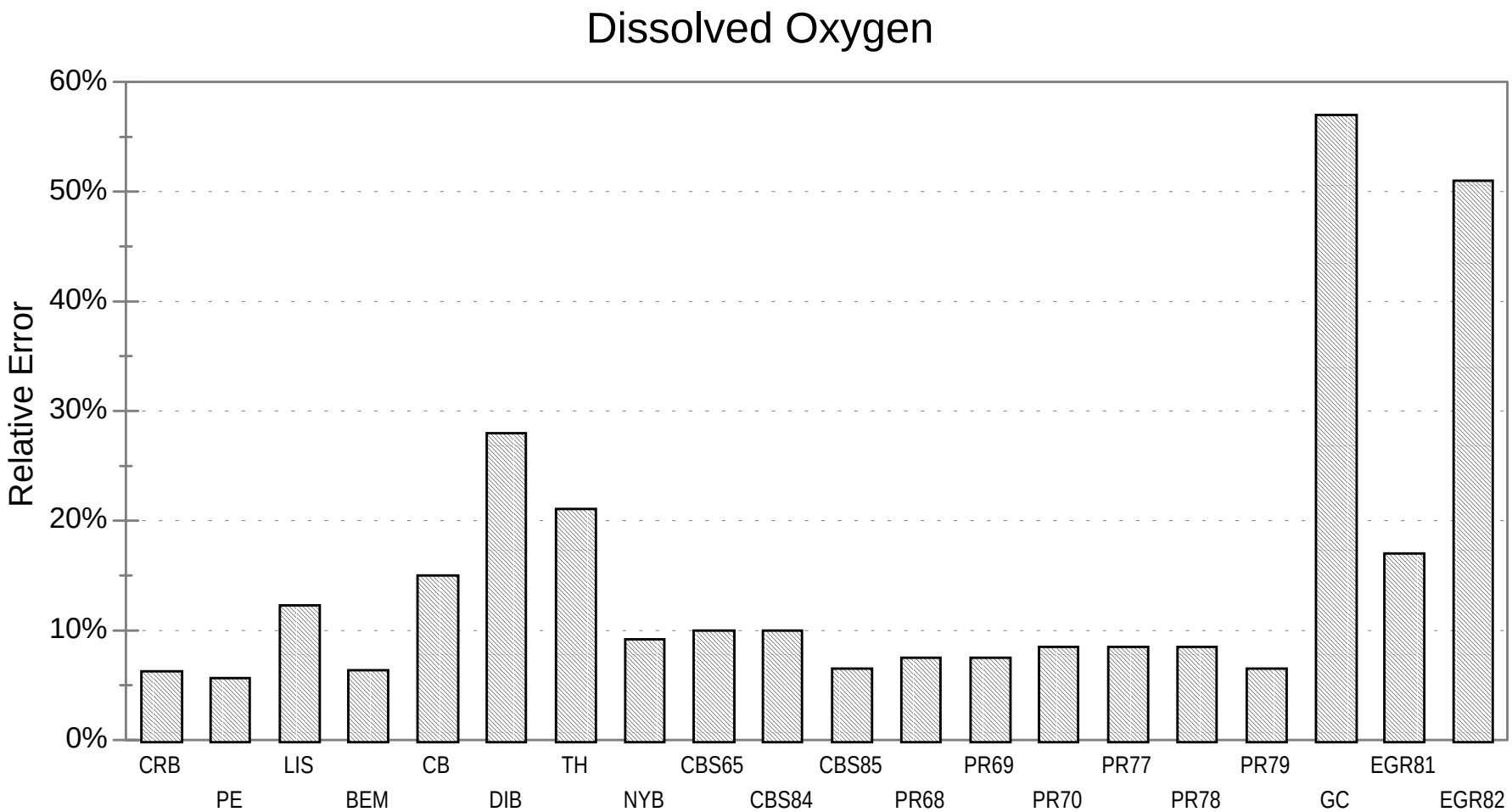
CALIBRATION RESULTS

- Results presented as longitudinal transect plots for the August period (low-flow condition)
- Results were also presented as time-series plots at a single station on the major tributaries
- Model statistics compare well with other similar studies


CHRISTINA RIVER BASIN MODEL: MAY - SEP 1995 VALIDATION
NITRATE NITROGEN (mg/L)
0
1
2
3
4
5
6
7
8
9
10
120
150
180
210
240
270
JULIAN DAY (MAY 1 TO SEP 21, 1995)
White Clay Creek (Cell 19,18)
OBSERVED
DAILY AVERAGE
DAILY MAXIMUM
DAILY MINIMUM


CHRISTINA RIVER BASIN MODEL: MAY - SEP 1995 VALIDATION
DISS ORTHOPHOSPHATE (mg/L)
1.0
0.8
0.6
0.4
0.2
0.0
120
150
180
210
240
270
JULIAN DAY (MAY 1 TO SEP 21, 1995)
White Clay Creek (Cell 19,18)
OBSERVED
DAILY AVERAGE
DAILY MAXIMUM
DAILY MINIMUM


CHRISTINA RIVER BASIN MODEL: MIN/MAX DISSOLVED OXYGEN AT USGS STATIONS
Dissolved Oxygen (mg/L)
0
2
4
6
8
10
12
14
16
120
150
180
210
240
270
JULIAN DAY (MAY 1 TO SEP 21, 1997)
DOWNINGTOWN GAGE (Cell 54,55)
03/07/00 1:41:32 p.m.
OBSERVED
DAILY AVERAGE
DAILY MAXIMUM
DAILY MINIMUM

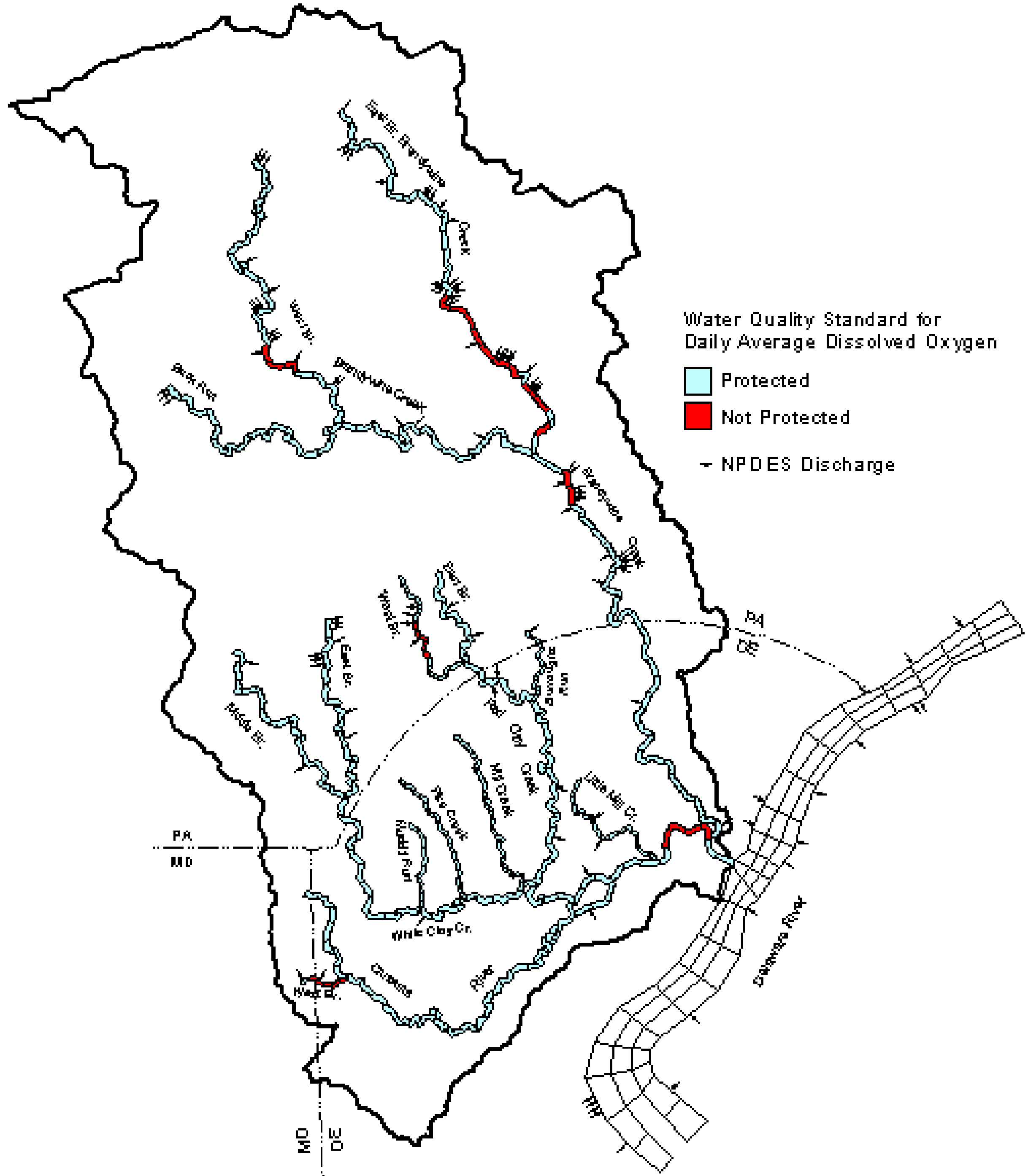

Dissolved Oxygen
Relative Error
60%
50%
40%
30%
20%
10%
0%
CRB
PE
LIS
BEM
CB
DIB
TH
NYB
CBS65
CBS84
CBS85
PR68
PR69
PR70
PR77
PR78
PR79
GC
EGR81
EGR82

LOW-FLOW TMDL ANALYSIS

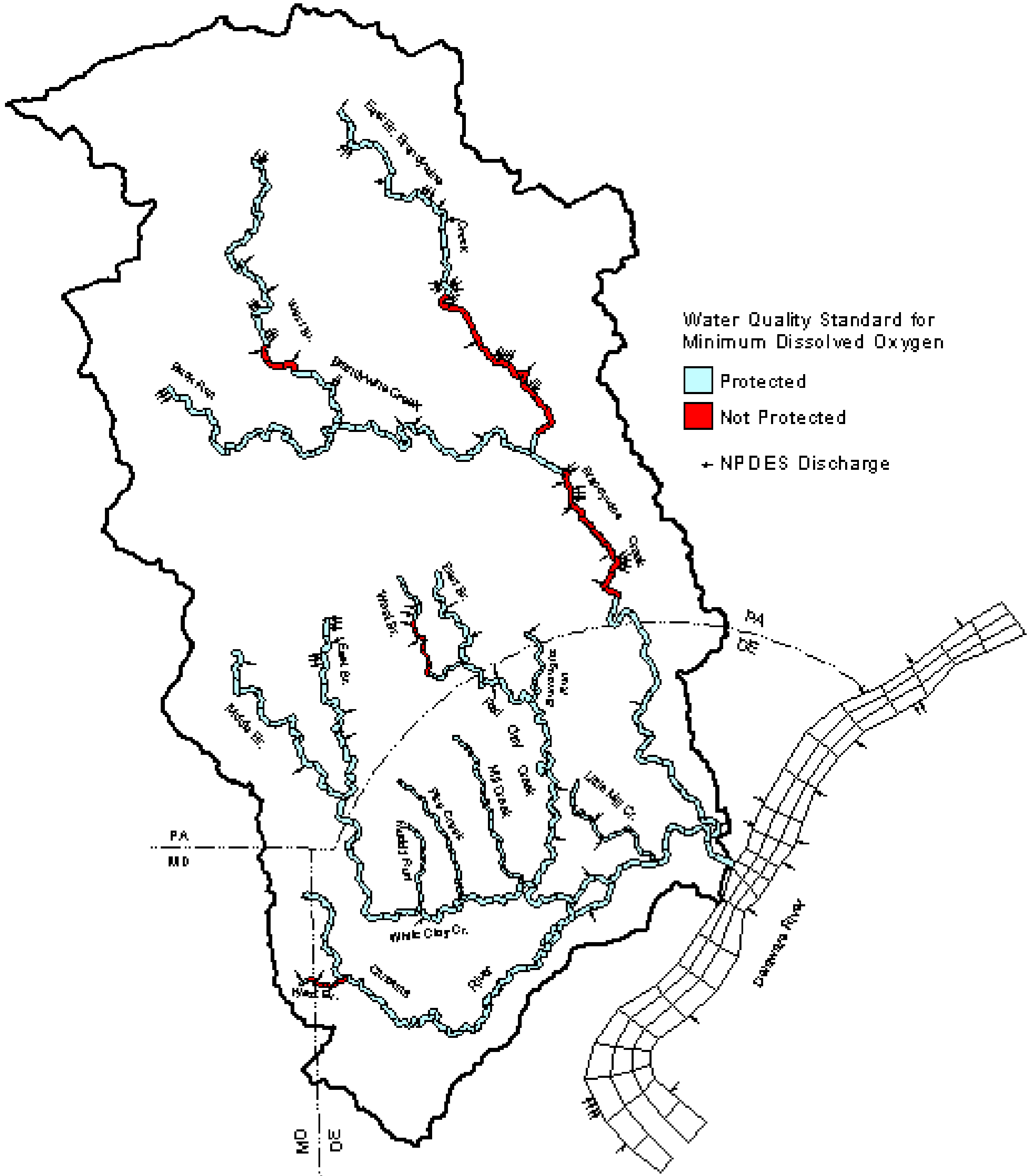
- Nonpoint source loads computed based on estimated 7Q10 flow rates
- Point sources set to their existing permit limits for both flow and concentration of CBOD, NH3-N, TP, and DO
- Stream conditions set to 7Q10 flow rates
- Stream temperature set to 75th percentile summer conditions

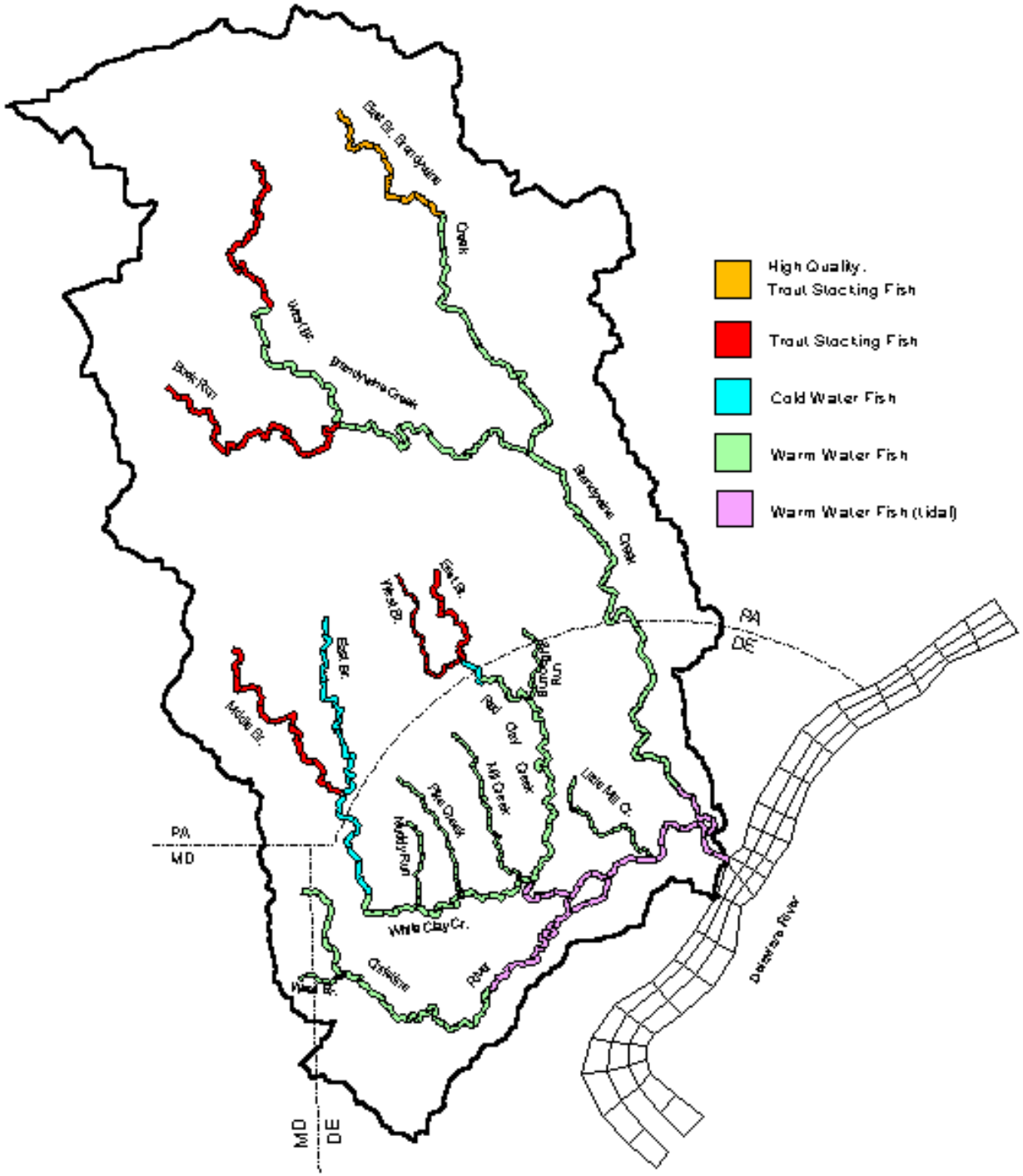
LOW-FLOW DATA SET

- 7Q10 flows estimated for each HSPF watershed based on nearby stream gages to compute a unit flow (cfs/sq.mi.)
- Nonpoint source loads were estimated for each of the 39 HSPF watersheds and distributed to the EFDC grid cells within those watersheds
- Water withdrawals were set to either the safe yield or 75% of the peak withdrawal rate



Water Quality Standard for
Daily Average Dissolved Oxygen
Protected
Not Protected
NPDES Discharge
PA
DE
PA
MD
MD
DE
White Clay Cr.


Water Quality Standard for
Minimum Dissolved Oxygen
Protected
Not Protected
NPDES Discharge
PA
DE
PA
MD
MD
DE
White Clay Cr.
Delaware River


High Quality, Trout Stocking Fish
Trout Stocking Fish
Cold Water Fish
Warm Water Fish
Warm Water Fish (tidal)
East Br. Brandywine
Creek
West Br.
Brandywine Creek
Birch Run
Brandywine
Creek
PA
DE
East Br.
West Br.
Middle Br.
Red Clay Creek
Mill Creek
Little Mill Cr.
Pike Creek
Mill Run
White Clay Cr.
Christina
River
Delaware River
PA
MD
MD
DE

TMDL Endpoints

Parameter	Target Limit	Reference
Daily Average DO, freshwater, Pennsylvania	5.0 mg/L	Pennsylvania Water Quality Standards
Daily Average DO, freshwater, Delaware	5.5 mg/L	Delaware Water Quality Standards
Daily Average DO, tidal waters, Delaware	5.5 mg/L	Delaware Water Quality Standards
DO at any time, freshwater, Maryland	5.0 mg/L	Maryland Water Quality Standards
Minimum DO	4.0 mg/L	Pennsylvania and Delaware Water Quality Standards
Nitrate Nitrogen, Pennsylvania	10.0 mg/L as N	Pennsylvania Water Quality Standards
Ammonia Nitrogen, Pennsylvania	function of Temp, pH	Pennsylvania Water Quality Standards

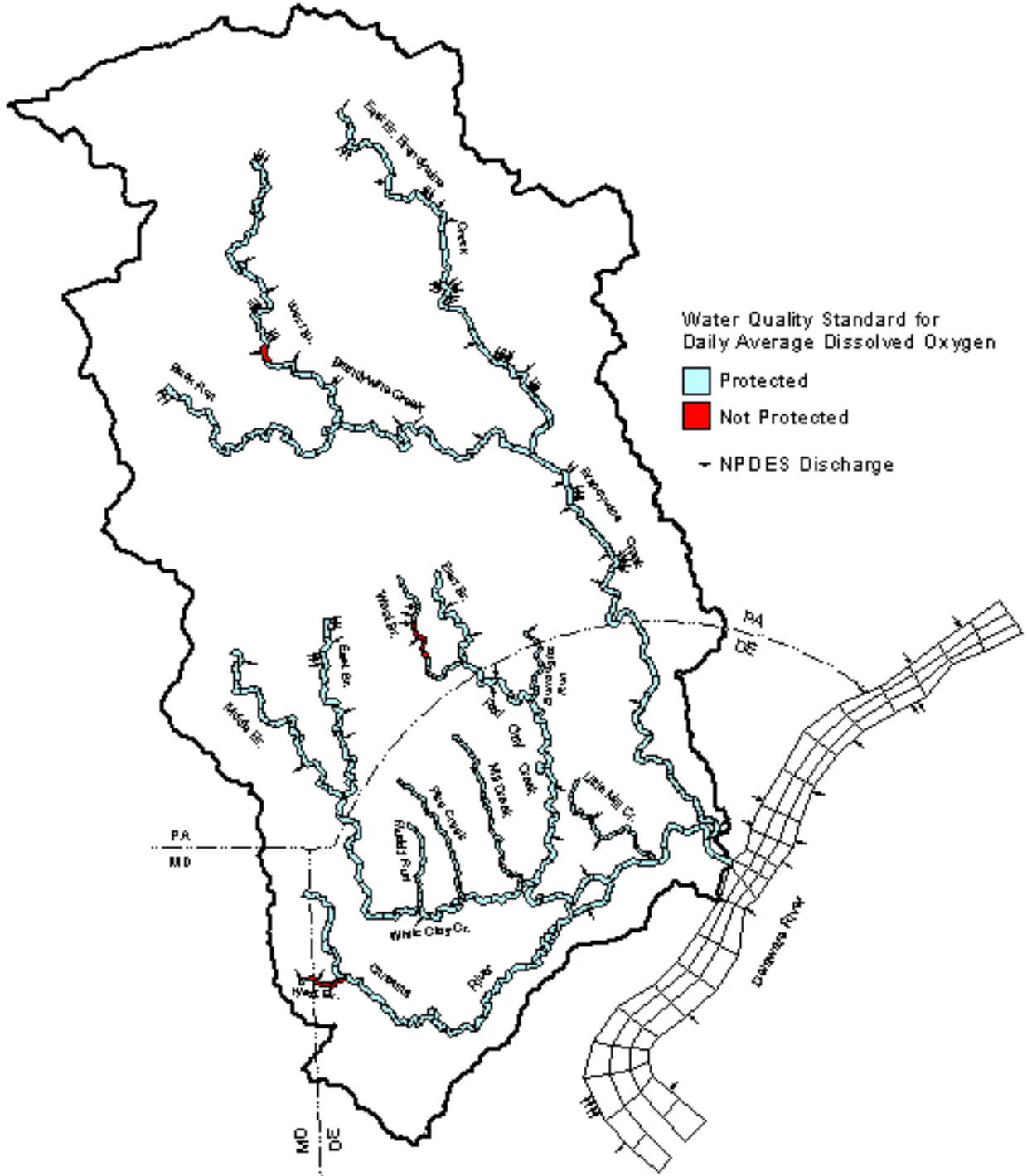
EMPR Allocation Strategy

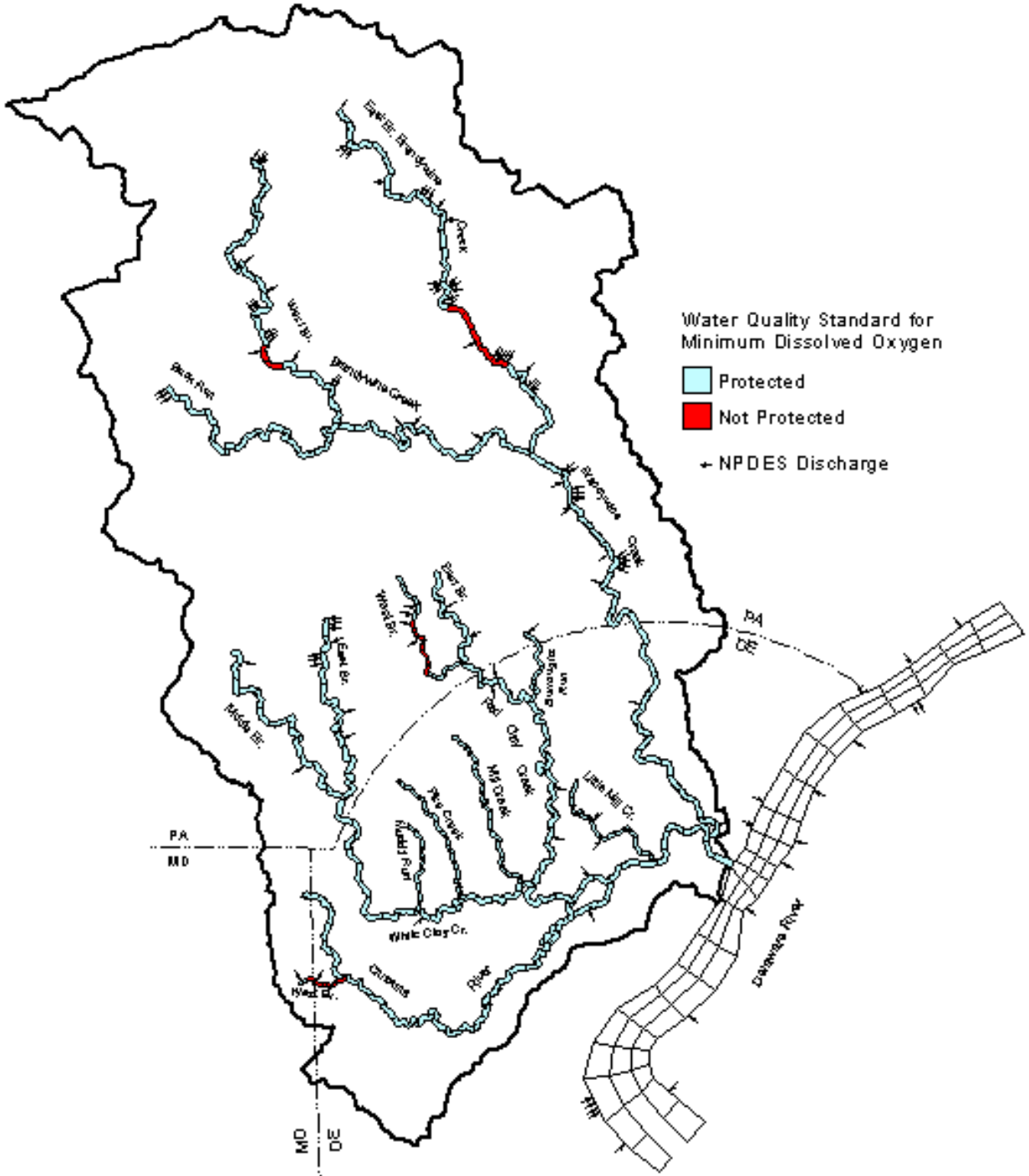
- Equal Marginal Percent Removal
- Tier 1
  - Analyze each NPDES discharge individually to determine if water quality standards are met
  - Set other tributaries and point sources not being considered to a baseline (background) condition
  - If an individual point source does not meet WQS, then reduce the CBOD, TN, TP load until WQS are achieved
- Tier 2
  - Add other discharges to the analysis one at a time based on the size of the mass load of CBOD
  - If WQS are not met, reduce CBOD, TN, TP load for all point sources in the analysis by equal percent

BASELINE CONDITIONS

- Based on 10th percentile concentrations for the main subwatersheds over the period 1988-1998 (STORET)
- Agreement with Omernik (1977) study of watersheds in the eastern U.S.

Subwatershed	Total Nitrogen (mg/L)		Total Phosphorus (mg/L)	
	Baseline	Omernik (1977) (67% range)	Baseline	Omernik (1977) (67% range)
Main stem and East Branch Brandywine Creek	1.56	0.33 - 6.64	0.01	0.008 - 0.251
West Branch Brandywine Creek	2.44	0.33 - 6.64	0.03	0.008 - 0.251
Red Clay Creek	2.65	0.33 - 6.64	0.05	0.008 - 0.251
White Clay Creek	2.31	0.33 - 6.64	0.02	0.008 - 0.251
Christina River	1.08	0.33 - 6.64	0.02	0.008 - 0.251


Water Quality Standard for
Daily Average Dissolved Oxygen
Protected
Not Protected
NPDES Discharge
East Br. Brandywine Creek
West Br.
Brandywine Creek
Beaver Run
Middle Br.
East Br.
West Br.
East Br.
Red Clay Creek
Mill Creek
Little Mill Cr.
Pike Creek
Muddy Run
White Clay Cr.
Christina River
Delaware River
PA
MD
DE
PA
DE
MD
DE


Water Quality Standard for
Minimum Dissolved Oxygen
Protected
Not Protected
← NPDES Discharge
Brandywine Creek
Christina River
Delaware River
White Clay Cr.
Red Clay Creek
Mill Creek
Little Mill Cr.
Shellpot Creek
Naamans Creek
Stoney Run
Middle Br.
East Br.
West Br.
PA
MD
DE

EMPR Tier 1 Allocations

NPDES Facility	Flow (mgd)	Existing Permit Limits			Tier 1 Allocation Limits			Tier 1 Percent Reduction		
		CBOD5 (mg/L)	NH3-N (mg/L)	TP (mg/L)	CBOD5 (mg/L)	NH3-N (mg/L)	TP (mg/L)	CBOD5	NH3-N	TP
PA0026531	7.0	10	2.0	2.0	10	2.0	1.6	0%	0%	20%
PA0026859	3.85	15	2.0	2.0	10.5	2.0	1.0	30%	0%	50%
PA0024058	1.1	25	3.0	7.5*	17.5	2.1	1.35	30%	30%	82%
MD0022641	0.45	22	6.45*	1.0	10	2.0	0.65	55%	69%	35%

EMPR Tier 2 Allocations

NPDES Facility	Flow (mgd)	Tier 1 Allocation Limits			Tier 2 Allocation Limits			Tier 2 Percent Reduction		
		CBOD5 (mg/L)	NH3-N (mg/L)	TP (mg/L)	CBOD5 (mg/L)	NH3-N (mg/L)	TP (mg/L)	CBOD5	NH3-N	TP
East Branch Brandywine Creek										
PA0026018	1.8	25	2.5	2.0	23.48	2.35	1.88	6%	6%	6%
PA0043982	0.4	25	0.10*	2.0	22.27	0.10**	1.78	11%	0%	11%
PA0012815	3.0	34	6.0	1.0	20.06	3.54	0.45	41%	41%	55%
PA0026531	7.0	10	2.0	1.6	5.90	1.18	0.73	41%	41%	64%
PA0030228	0.0225	7.0	1.0	3.0	6.86	0.98	2.94	2%	2%	2%
PA0054917	0.003	7.0	1.0	1.0	6.86	0.98	0.98	2%	2%	2%
PA0050458	0.0351	10	3.0	1.0	9.80	2.94	0.98	2%	2%	2%
PA0050547	0.0375	10.0	3.0	1.0	9.80	2.94	0.98	2%	2%	2%

EMPR Tier 2 Allocations

NPDES Facility	Flow (mgd)	Tier 1 Allocation Limits			Tier 2 Allocation Limits			Tier 2 Percent Reduction		
		CBOD5 (mg/L)	NH3-N (mg/L)	TP (mg/L)	CBOD5 (mg/L)	NH3-N (mg/L)	TP (mg/L)	CBOD5	NH3-N	TP
West Branch Brandywine Creek										
PA0029912	0.1	25	20.0	2.0	24.72	19.78	1.98	1%	1%	1%
PA0036987	0.39	25	7.0	2.0	24.72	6.92	1.98	1%	1%	1%
PA0026859	3.85	10.5	2.0	1.0	8.08	1.54	0.77	23%	23%	23%
PA0011568-001	0.5	30*	0.50*	0.30*	23.10	0.50**	0.30**	23%	0%	0%
PA0011568-016	0.5	30*	0.50*	0.30*	23.10	0.50**	0.30**	23%	0%	0%
PA0055697	0.049	25	1.50*	2.0	24.25	1.46	1.94	3%	3%	3%
PA0044776	0.6	15	3.0	2.0	13.83	2.77	1.84	8%	8%	8%
West Branch Red Clay Creek										
PA0024058	1.1	17.5	2.1	1.35	16.62	1.99	1.28	5%	5%	5%
PA0057720-001	0.05	10	2.0	2.0*	9.50	1.90	1.90	5%	5%	5%
Christina River West Branch										
MD0022641	0.45	10	2.0	0.65	9.22	1.86	0.60	7%	7%	7%
MD0065145	0.05	15	4.52*	1.0	13.95	4.20	0.93	7%	7%	7%